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AN ANALYSIS OF SOME ANALYTICAL FERROGRAPHY DATA

by

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AN ANALYSIS OF SOME ANALYTICAL FERROGRAPHY DATA

by

H. Larson and T. Jayachandran

ABSTRACT

This paper presents a statistical analysis of data collected from a controlled experiment utilizing several laboratories, fluid sources and ferrograms. Emphasis is placed on the ability to use numerical measurements to arrive at consistent conclusions, from one ferrogram to another, and from one laboratory to another.

Analytic ferrography is a method for examining wear debris in a lubricant sample. The lubricant is pumped over a glass substrate which is positioned over a magnetic field of varying strength along the length of the substrate. The varying strength is meant to precipitate magnetic and ferromagnetic wear debris according to mass/size over the length of the substrate. The material deposited is then rinsed and fixed to the substrate, allowing optical analysis of the wear particulates. This optical analysis allows examination of the shapes and sizes of the debris deposits, and subjective evaluations of their compositions and the mechanisms which created them. This type of examination has proved useful in characterizing various wear regimes of many types of equipment. Such visual slide inspections hold promise for providing useful information which complements spectrometric analysis of the fluid, since the opticly visible debris deposits on the substrate typically fall in size ranges which exceed those that affect the spectrometer measurements.

It is also possible to use light reflected/light transmitted densitometers to derive quantitative measures of the debris deposited on a ferrogram. These measurements indicate the percentage of blocked area in a microscopic field of view. As the field of view is moved along the length of the slide, the typical sizes of particles are expected to change, because of the magnetic field employed in the preparation of the slide. It would be ideal if these

quantitative densitometer readings could be used in some way to accurately characterize the distribution of wear particle sizes in the original lubricant sample.

Densitometer readings are affected by many variables including the original substrate preparation; such things as sample dilution, amount of lubricant pumped over the substrate, viscosity of the lubricant as well as the particle size and type distribution in the lubricant can obviously have an effect on the densitometer numbers observed. In addition, the type of densitometer used and the care used in its calibration, as well as the exact location of the field of view in the approximately 55mm by 4mm substrate area, could certainly be expected to affect a densitometer reading.

During the 1970's several different analytic ferrography procedures were adopted by different groups; differences in technique included the density lighting method and reading techniques to be employed with the ferrogram. Preliminary studies showed that wide variations in readings existed at least in part because of differing techniques employed. This led to attempts to standardize the technique to employ, to hopefully improve the accuracy and repeatability of the densitometer readings.

Reference [3] describes a two stage investigation into analytic ferrography standardization conducted in 1981. A total of six laboratories participated in this study. In stage I, each of 3 laboratories provided bulk fluid samples;

these laboratories were selected on the basis of their experience with a particular fluid type. One of the laboratories submitted mineral lubricant material, one submitted synthetic lubricant material and the final one submitted mineral-based hydraulic fluid. Six bottles of fluid were prepared from each bulk sample fluid; one of these bottles (of each type) was sent to the six participating laboratories (which include the 3 laboratories that submitted the bulk fluids). Each participating laboratory was to follow strict rules in preparing 5 ferrograms (slides) from each bottle received, making 15 ferrograms for each laboratory. Each prepared ferrogram was used 5 times (in a standardized way) to make densitometer readings (only by the laboratory which had prepared it); the densitometer readings were made at 10 locations down the length of the ferrogram. Thus each laboratory produced 3 x 5 x 5 x 10 = 750 densitometer values (3 fluid types, 5 ferrograms of each, 5 readings of each ferrogram at 10 locations). Presumably, this stage I data should prove useful in examining how densitometer readings may vary from one slide to another, and from one laboratory to another, when each laboratory was charged with preparing its own ferrograms in the same way from the same fluid source.

Stage II of the investigation involved the laboratories reading the same slides. In this part of the investigation, a total of six slides were prepared; two slides were made from each of the three different fluid types. These same six

slides were then routed in turn to each of the six laboratories. Each laboratory made 5 densitometer readings of each slide, again at each of 10 different positions, for a total of 300 different densitometer readings at each laboratory. This set of data should contain information about how well different laboratory readings will agree, granted they analyze the same slides.

We were provided the data from five of the six laboratories, for both of these stages, and asked to see what our conclusions would be about the use of densitometer readings as an objective way to analyze ferrograms. If densitometer readings from ferrograms are to be a useful objective tool in their own right, it would seem important to investigate how well two different laboratories could communicate with each other, having made its own ferrogram from the same fluid source. We shall use the stage I data to investigate this type of question. A closely related question involves how well two different laboratories could communicate in making densitometer readings from the same ferrogram; here possible differences in the ferrograms to be read do not occur. We shall use the stage II data to investigate this question.

In the stage I study, each of the five laboratories received bottles of fluid from the same sources: one bottle each of a mineral lubricant, a synthetic lubricant and a hydraulic fluid. For reasons unknown to us, the data from the

sixth laboratory were not provided. Each of these laboratories prepared five ferrograms from each fluid and then made five sets of densitometer readings from each of its own ferrograms, at 10 positions along the length of the ferrogram. Since position along the ferrogram should in theory be related to the size/mass distribution of particles in the fluid, one could use comparisons of these distributions over positions to measure differences in ferrograms and laboratories. However we feel a components of variance model, adopted separately for each position, gives a more transparent and, in some senses, more appealing way of investigating ferrogram and laboratory differences. Thus, for any specific position along the ferrogram let y_{ijk} represent the densitometer reading made by laboratory i, from the $k^{\underline{th}}$ repetition of reading ferrogram j. A simple components of variance model (see [2] for discussions of this type of model) then specifies that

$$(1) \quad y_{ijk} = \mu + \ell_i + s_{ij} + r_{ijk}, \quad \begin{matrix} i = 1,2,\ldots,5 \\ j = 1,2,\ldots,5 \\ k = 1,2,\ldots,5 \end{matrix}$$

The parameter μ represents the overall average reading at this position (for the fluid type), the parameter ℓ_i, represents the contribution to the reading made by laboratory i, the parameter s_{ij} is the contribution from the $j^{\underline{th}}$ ferrogram made by laboratory i and r_{ijk} is the contribution from the $k^{\underline{th}}$ replication of the $j^{\underline{th}}$ ferrogram made by laboratory i. The standard components of variance model assumes the ℓ_i

values are normal random variables with mean 0, variance σ_ℓ^2, the s_{ij} values are normal random variables with mean 0 and variance σ_s^2, and finally the r_{ijk} values are normal random variables with mean 0, variance σ_r^2; all distinct pairs of ℓ_i, s_{ij}, r_{ijk} variables are assumed to be independent. A consequence of this model, then, is that the individual y_{ijk} values are normal with mean μ and variance $\sigma_\ell^2 + \sigma_s^2 + \sigma_r^2$. The standard components of variance analysis then allows one to use the observed data to estimate σ_ℓ^2, σ_s^2 and σ_r^2 and to further investigate questions which may be of interest.

Recall that the same model is applied to each of the 10 positions individually, thus giving 10 separate estimates for each of these parameters. While there do seem to be important position differences in the estimates, especially for the synthetic and hydraulic fluids, we shall simply discuss the estimates and their uses, having averaged their values over the 10 positions. Table 1 presents the estimates of σ_ℓ^2, σ_s^2 and σ_r^2, based on the stage I data, for the three fluid types.

Table 1

Fluid type	Estimated value for σ_ℓ^2	σ_s^2	σ_r^2
Mineral	112.6	15.4	1.4
Synthetic	527.4	54.0	5.2
Hydraulic	779.2	248.7	5.2

The estimated variance between repeated readings of the same ferrogram (σ_r^2) is considerably smaller than the estimated variance from one ferrogram to another (σ_s^2), which itself is considerably smaller than the estimated variance from one laboratory to another (σ_ℓ^2), for each fluid type. The fact that σ_s^2 and σ_ℓ^2 appear to be relatively large has important implications regarding the sole use of densitometer readings in making decisions about the fluid sampled. Suppose, for example, a sample of fluid is taken from a piece of equipment and its condition (or "health") is to be assessed on the basis of a densitometer reading. The simplest kind of rule for this sort of situation is one in which an extreme value C is determined; if the densitometer reading exceeds C (implying the amount of a particular particle size is "large") the equipment condition is judged poor and maintenance should be performed. Does this type of rule appear feasible in light of the values in Table 1 ?

The stage I data can be used in either of two ways to address this question, both leading to the same conclusion

(a) Suppose a laboratory prepares two different ferrograms from the fluid. Is the same number C appropriate for readings from either ferrogram?

(b) Suppose two different laboratories each prepare a ferrogram from the fluid. Is the same number C appropriate for readings from either ferrogram?

The answer in both cases is no, as the following reasoning will illustrate.

It is well known (see [1]) that if X and Y are independent

normal random variables each with the same mean μ and variance σ^2, the expected value of the magnitude of the difference X-Y is $\frac{2\sigma}{\sqrt{\pi}}$. For case (a) let X represent the reading from the first ferrogram and let Y represent the reading from the second ferrogram (same laboratory). From the components of variance model, equation (1), this difference is

$$X-Y = (\mu + \ell_1 + s_{11} + r_{111}) - (\mu + \ell_1 + s_{12} + r_{121})$$

$$= (s_{11} + r_{111}) - (s_{12} + r_{121})$$

since μ and the laboratory parameter cancel off. Thus, in this case, the difference X-Y is the same as the difference of two normal variables each having variance $\sigma_s^2 + \sigma_r^2$; the expected magnitude of the difference of the two readings then is $2\sqrt{\frac{\sigma_s^2 + \sigma_r^2}{\pi}}$ when both ferrograms are made by the same laboratory. In case (b), the components of variance model gives $X-Y = (\ell_1 + s_{11} + r_{111}) - (\ell_2 + s_{21} + r_{211})$ for the difference of two readings, where each of two different laboratories makes its own ferrogram from the same source; now the laboratory parameters do not cancel off and X-Y is the same as the difference of two normal variables each with variance $\sigma_\ell^2 + \sigma_s^2 + \sigma_r^2$. The expected magnitude of the difference of the two readings is in this case $2\sqrt{\frac{\sigma_\ell^2 + \sigma_s^2 + \sigma_r^2}{\pi}}$

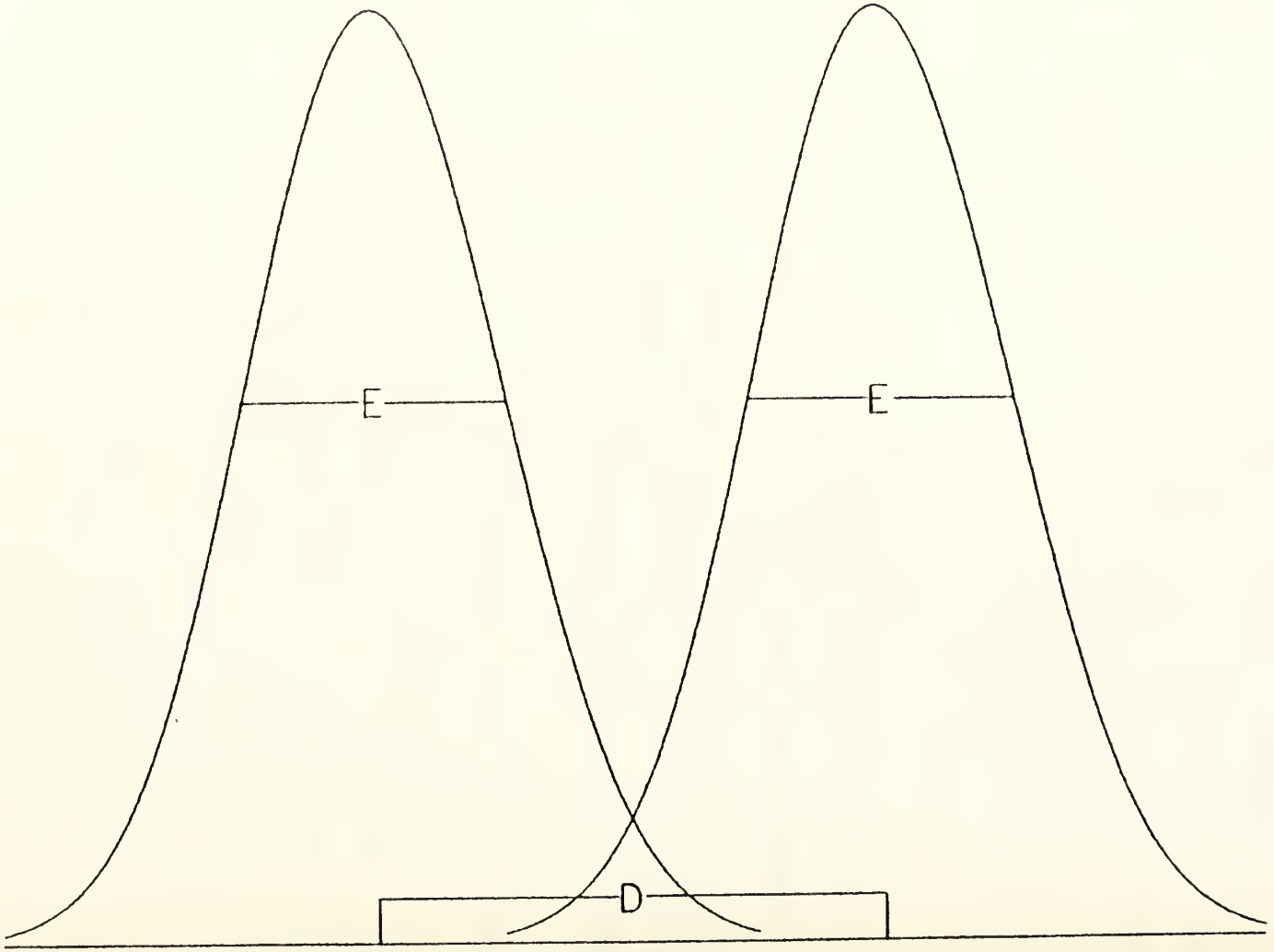
Table 2 presents the estimates of these expected magnitudes, using the values from Table 1.

Table 2

Fluid type	Expected difference in magnitude	
	Same lab	Different lab
Mineral	4.6	12.8
Synthetic	8.7	27.3
Hydraulic	18.0	36.3

Any individual reading can be thought of as an observation from a normal distribution with standard deviation σ_r; this value is estimated to be $\sqrt{1.4} = 1.2$ or $\sqrt{5.2} = 2.3$, depending on the fluid type, from Table 1. In figure 1, this individual reading variability is represented by the bell shaped curves labelled E. The expected magnitude of the difference of readings from two ferrograms, either made by the same or different laboratories, is represented by D in this figure; the estimated value of D comes from Table 2, again depending on fluid type, and whether the same laboratory is involved in making the two densitometer readings. On the average, one would expect one of the two densitometer readings to lie under the bell shaped curve on the left and the other to lie under the bell shaped curve on the right. For any of the fluid types (whether made by the same laboratory or not) the magnitude of D relative to E is quite large; a densitometer reading which looks extreme from one distribution may appear quite reasonable from the other. It does not appear feasible to specify densitometer limits which are useful in identifying

FIGURE 1



extreme cases of a particular particle size, for 2 different ferrograms, whether made by the same laboratory or not.

A very similar analysis has been done for the stage II data. Recall that in stage II, six different ferrograms were prepared (two for each fluid type). All of the six slides then were sent in turn to each participating laboratory; each laboratory made 5 readings (at 10 positions) for each slide. This data allows one to examine how closely the densitometer readings might be from different laboratories, where now all five laboratories are using the same ferrogram. It is not known whether the two slides of the same type (mineral, synthetic, hydraulic) actually came from the same source or from different sources (in which case the distributions over the two slides might be expected to differ). For this reason separate analyses have been done for the six slides; again each analysis refers to a particular position on the slide, and the pertinent estimated variances were then averaged over positions and slides. For the densitometer reading, at a given position on a given slide, let y_{ij} represent the reading by laboratory i, repetition j. We assume that

$$y_{ij} = \mu + \ell_i + r_{ij} \quad , \quad i = 1,2, \ldots,5, \quad j = 1,2,\ldots,5;$$

as earlier, ℓ_i represents the contribution of laboratory i and r_{ij} is the contribution of the $j^{\underline{th}}$ replication from laboratory i. It is assumed that the ℓ_i values are independent normal, mean 0, variance σ_ℓ^2, and the r_{ij} values

are independent, normal with mean 0, variance σ_r^2. Again, this is a standard components of variance model (see reference [2]); the data from the same five laboratories, stage II, produce the estimates given in table 3.

Table 3

Fluid type	Estimated value for σ_ℓ^2	Estimated value for σ_r^2	Expected magnitude of difference
Mineral	2.5	2.0	2.4
Synthetic	23.2	2.0	5.7
Hydraulic	33.6	2.8	6.8

The parameter σ_r^2 for this stage II data is the same as σ_r^2 for the stage I data, so we would expect the estimates from the two cases to be not too different. As is evident from comparing the values in tables 1 and 3, the stage II estimate for mineral is higher than in stage I and the estimates are lower for the other 2 fluids. The mineral estimates are close enough together to seem reasonable, for the sample sizes used. The estimates are considerably lower in stage II than stage I, for the other two fluids; it is not known why this should be the case, unless the laboratories were possibly more careful in the later (stage II) study. The paramenter σ_ℓ^2 for the stage II data does not measure the same thing as σ_ℓ^2 for the stage I data, although the same symbol is used. Recall that in stage I each laboratory prepared

and read only its own ferrograms, although all were made from the same source; in stage II the laboratories got their densitometer readings from exactly the same ferrograms, so there was no possible variability in initial preparation of the slides. Thus one would expect the variability between the laboratories to possibly be smaller in stage II than in stage I; that this is indeed true for the estimates can be seen by comparing the entries in tables 1 and 3.

Using the same reasoning discussed earlier, for the expected magnitude of the difference of two normal random variables, we would expect the magnitude of the difference of readings made by two different laboratories to be $\sqrt{\frac{\sigma_\ell^2 + \sigma_r^2}{\pi}}$. The estimates of these quantities are also given in Table 3 for the three fluid types. These quantities again can be thought of as values for D in figure 1, whereas the values of E are the estimates of σ_r, $\sqrt{2} = 1.4$ or $\sqrt{2.8} = 1.7$ depending on fluid type. Again the conclusion must be generally negative, regarding whether two laboratories could use the same criterion and reach the same decision, based solely on their own densitometer readings from the same ferrogram.

The discussion of densitometer readings given here refers only to comparisons of densitometer readings as made in the study described in [3]. It should not be construed as critical of the use of ferrograms in general as a tool for studying wear mechanisms. Rather, this set of observed data simply

says that sole reliance on desitometer readings is not likely to lead to useful procedures for describing or comparing wear mechanisms, with the preparation and reading methods employed in the study described in [3].

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